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14. ABSTRACT
This project investigated technologies to enable autonomous flight of agile vehicles in urban environments. Specifically, technologies were developed that related to vision-based feedback for control. The mission profile under consideration was a single vehicle carrying a video camera while flying below the rooftops of a city with no additional sensors or pre-existing map information. As such, substantial progress was made in the areas of feature-point tracking, state estimation, scene reconstruction, robustness to camera calibration, daisy-chaining navigation, mapping, path planning, and feedback characterization. An integrated approach was used that focused on multi-disciplinary analysis for decision making and control commands. The project spiraled the maturation of technologies from theory to simulation to flight testing. The simulation relied upon a hardware-in-the-loop simulation facility that allowed the physical camera to record measurements from high-fidelity graphics and thus consider the effects of distortion and nonlinearities. ~~The flight testing used a set of 24-inch wingspan vehicles carrying a~~

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Grant Report

Vision-Based Control of Agile, Autonomous Micro Air Vehicles and Small UAVs in Urban Environments

F49620-03-1-0381

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1 Introduction

This report documents research performed under the contract entitled, "Vision-Based Control of Agile, Autonomous Micro Air Vehicles and Small UAVs in Urban Environments." This project was a 5-year effort meant to mature technologies related to vision-based feedback to enable autonomous operation within urban environments.

The technical achievements from this project was quite substantial in that many contributions were made to a variety of disciplines. In particular, substantial progress was made in the areas of feature-point tracking, state estimation, scene reconstruction, robustness to camera calibration, daisy-chaining navigation, mapping, path planning, and feedback characterization. An integrated approach was used that focused on multi-disciplinary analysis for decision making and control commands.

The project spiraled the maturation of technologies from theory to simulation to flight testing. The simulation relied upon a hardware-in-the-loop simulation (HILS) facility that allowed the physical camera to record measurements from high-fidelity graphics and thus consider the effects of distortion and nonlinearities. The flight testing used a set of 24-inch wingspan vehicles carrying a commercial autopilot while a laptop analyzed video and generated guidance commands via telemetry. The resulting setup was able to achieve some level of mission capability while demonstrating both the strengths, and numerous unsolved challenges, for vision-based control of aerial robotics.

Additionally, the project has further developed and matured the relationahip between the Air Force, and particularly Eglin Air Force Base, with the research team. The satellite campus known as the REEF has shown value as a hub for collaboration between academia and industry to the Air Force. The combination of a visualization laboratory and micro air vehicle facilities, along with a technical workforce, is a formidable pairing that will continue to advance mission capabilities of aerial robotics for the warfighter.

2 Summary of Results

2.1 Academic Goals

The academic goals related to the education and training of students. As such, the granting of degrees along with publishing of academic papers are valuable metrics with which to evaluate the academics. The project showed particularly strong growth in this area due to the extended continuity of funding that allowed students to mature while working on the same research project throughout their studies.

The team initially hired several new students in 2003 who remained on the project until their graduation with a PhD degree in 2007. The following tables relates the number of students who were primarly funded off this grant.

	2003	2004	2005	2006	2007
M.S.	3	8	7	2	2
Ph.D.	0	1	2	1	8

The publishing of papers occured in both conferences and journals. A strong growth is again demonstrated that indicates conference papers were transitioned into journal papers during the final years of the grant.

	2003	2004	2005	2006	review	preparation
conference	5	28	33	26	18	20
journal	0	3	9	4	14	8

2.2 Technology Transfer Goals

The team has pursued several avenues for technology transfer. Certainly the transition of technologies to the warfighter was a critical concern throughout the project. These various

- The team conducted a short course entitled "Vision-Based Control for Autonomous Vehicles" held at the AIAA Guidance, Navigation and Control Conference in August 2007. The 2-day course had 12 attendees from 4 countries.
- The team is preparing a textbook entitled "Active Vision Control for Agile Autonomous Vehicles" that will document much of the research for this grant. It will be distributed through AIAA with a pagecount sufficient to present material in more depth than can be obtained in a journal paper.
- The team has been participating on a number of SBIR and STTR programs in the areas of aeroelasticity, control, design, sensing, and dynamics.
- The tema has applied for a pair of patents on vehicle design and sensor analysis that directly result from this grant.

2.3 Programmatic Goals

The programmatic goals related primarily to the technical aspect of the project. The team investigated a number of challenges across several fields in a multi-discplinary fashion. The number of students and papers associated with this grant are certainly indicative of the resulting technical contributions.

- high-fidelity modeling of aeroelastic MAV wings
- data fusion of IMU/vision for robust vision
- multiresolution learning for scene reconstruction
- method to bound uncertainty in camera calibration
- nonlinear stability analysis for visual-servo control
- 3-D motion planning for mapping using sensor quality

A number of lessons were also learned in this project. These lessons learned are valuable contributions that will be used to guide future projects. In particular, the understanding of limitations in the technology and associated physical reasoning are quite useful.

- scale of aerodynamic/structure complicated for MAV
- noise is devastating for vision-based control

- interlaced cameras worse for noise than progressive cameras
- state estimation better for rotation than translation
- field of view can be constrictive for flight operations
- on-board hardware challenging for MAV

2.4 Collaboration Goals

The collaborative goals sought to foster a stronger relationship between academia and the Air Force. The team enforced compatibility, and often equality, in both hardware and software as a foundation to help collaboration. Also, the academics advised a number of military personnel in their pursuit of advanced degrees.

- Phil Webb of AFRL/MN
- Michael Kaiser of AFRL/MN
- Crystal Evans of Seek Eagle
- Tony Thomson of AFRL/MN
- Paul Wilson of AFRL/MN
- David Eaton of AFRL/MN
- Eric Duron of Seek Eagle